INFLUENCE OF THE MATERIAL HARDENING MODEL ON THE SIMULATION RESULTS FOR THE EQUAL CHANNEL ANGULAR EXTRUSION – ECAE – PROCESS

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Abstract: The objective of this article is to present a comparison of the results achieved for the Equal Channel Angular Extrusion – ECAE – process, using a so called *"quick start"* approach, followed by simulation using material parameters defined by Swift´s [1] and Voce´s [2] relations. The comparison was made considering extrusion force, equivalent stresses and equivalent plastic strain quantities. Two angles (90 and 120^o), two channel concordance radii relations (0.2, 2 and 2, 5mm) and two friction coefficients (0.05 and 0.15) were used. ANSYS 12.1 commercial package was applied for this work.

1 INTRODUCTION

Equal Channel Angular Extrusion – ECAE – is a powerful deformation technique that was first studied and developed by Segal in 1981 [3]. It is an innovative process that allows engineers and researchers to obtain improved mechanical properties for some materials, by forcing its passage through an angular channel with constant cross section. The improvement of the mechanical properties is a result of severe plastic deformation with consequent grain refinement. The advantage of this process is that the cross section of the material remains constant, and reduced forming forces are required when comparing to other cold working processes.

In recent years many researchers have investigated angular extrusion processes under experimental and numerical perspectives. Some works are focused on experimental techniques aiming to optimize die and process conditions and evaluate different materials. Numerical techniques and commercial FEM – Finite Element Method – packages have also been used to study specific details of the process in order to obtain better processing conditions and improved material characteristics.

Krishnmaiah *et al.* [4] applied the ABACUS commercial FEM package to study the process for 99.8% pure normalized cooper, in order to evaluate the influence of the friction coefficient on the die filling and in other mechanical properties. In their analysis, four-node elements in plane strain mode, with reduced integration were applied.

Aour *et al.* [5] numerically investigated polymer extrusion applying MARC FEM software, using also four-node elements and reduced integration. The work aimed at evaluating the results of the process in the form of equivalent plastic strain and process characteristics, such as channel angle, internal and external radii, friction coefficient and number of passages through the die.

Son, Jin and Im [6] applied FEM to investigate the influence of friction on the load required to perform the extrusion through an angular channel, and also on the strain distribution in the workpiece. In this case a mixed formulation was used, with linear tetrahedral elements, and constant shear friction. In this work, a remeshing process based on an effective strain measure was also applied.

Lee *et al.* [7] performed a non-isothermal 3D simulation of a titanium workpiece to evaluate the effect of process parameters on the strain distribution. Rotation of the workpiece in 90 and 180º between passages through the die was considered. In the 3D formulation of the problem, hexahedral and tetrahedral elements were used to model the workpiece and channel, respectively. A constant friction model was used combined to a rigid-thermo-visco plastic constitutive relation for the material.

Hu, Zhang and Pan [8] used FEM to optimize the die structure for the ECAE process for a magnesium alloy (AZ31). In their work, a rigid die was considered, and the workpiece was described by an elastic-perfectly plastic material. As process parameters, the friction coefficient, angle between channels and internal and external radii were accounted for.

Nagasekhar *et al.* [9] performed a comparative analysis between FEM simulation and experimental approach in order to verify the effectiveness of the computational model. The authors used pure cooper, which mechanical properties were evaluated using a standard stress-strain test. The result of the work is focused on the load required to perform the process. The simulation was performed using explicit 3D ABACUS software. Some process parameters, like the Coulomb friction coefficient, were also varied through the analysis. The authors also applied tetrahedral elements with reduced integration and adaptive meshing.

Kaushik, Karaman and Srinivasa [10] used FEM simulation to study the Cooper powder pressing with the ECAE process. In their work, the explicit ABACUS software was used. The material porosity was modeled using the Gurson [11] and Duva & Crow [12] models. The authors used the friction coefficient and interaction conditions as process parameters. They applied 2D and 3D formulations to evaluate specific process details.

Semiatin and Delo [13], studied the deformation and failure of several difficult-to-work alloys, like commercial-purity titanium and AISI 4340 steel during ECAE process. Their work was mostly experimental, but FEM was applied in order to study specific failure modes and the effects of chilling on non-uniform flow during non-isothermal ECAE.

Yang and Lee [14], used the commercial package MARC to analyze strain conditions after ECAE. They varied the channel angle and the extrusion direction during consecutive passages through the process. The effect of friction was also evaluated.

As it can be noticed, numerous works and analysis have been performed in recent years using FEM simulation as the main analysis tool. Different classes of materials were evaluated, and, in certain cases, experimental material evaluation was performed in advance to verify their mechanical properties. In most cases, the analysis aims to assess process characteristics for the different materials using numerical approach. In addition, the brief survey showed that, in simulations using a single passage, the main parameters that affect the workability of the materials in general, are the angle between the channels, the friction coefficient and the internal and external concordance radii.

In the industry perspective, in the search for new materials, optimized components and new strategies to design metal forming operations, oftentimes research engineers are confronted with no detailed material data to start the tooling development. In such conditions, it is not uncommon to use material properties, such as Young's modulus, Poisson's ratio, yield and ultimate stresses and elongation at rupture, obtained from general material libraries, tables, standards and even internet sources. This strategy is sometimes referred as "*quick start*" and has been used when no stress-strain curve for the material is available. For sure, there are some errors to be considered when taking this approach, instead of devising experiments to evaluate mechanical parameters of the material, and yield stress curves, such as Swift´s [1] and Voce´s [2] relations. This activity takes time and consumes laboratory resources.

The objective of this article is to present and discuss a comparison of numerical experiments performed for a given carbon steel, using constitutive parameters determined via classical approaches and parameter identification techniques. The Swift´s [1] parameters were determined using tensile tests by assuming uniform stress-strain distribution within the specimen, whereas a parameter identification technique [15] was used in conjunction with a modified Voce´s [2] equation.

2 HARDENING MODELS

The *"quick start"* using FEM usually considers two hardening models: elastic-perfectly plastic and bilinear hardening [16]. The former requires only three properties, which can be easily found for general materials in many references (books and internet sites): the Young's modulus, Poisson's ratio and Yield Strength. The model considers that, once the equivalent stress in the simulation reaches the material yield stress, the material presents perfect plasticity. The latter requires two additional properties: Ultimate Stress and Elongation at breakage. This makes it possible to establish the bilinear hardening model for the material, computing the Tangent Hardening Modulus and approximating the real material hardening behaviour by two linear curves, as shown in Figure 1.

The material chosen for this analysis is the same used in Stahlschmidt *et al*. [17], which is a cold rolled carbon steel without further heat treatment. In the work, the authors used a parameter identification methodology based on optimization, to determine hardening parameters of a modified Voce [2] yield stress curve. The basic properties considered for the *"quick start"* hardening models were obtained from MatWeb website [18] and are presented in the Table 1.

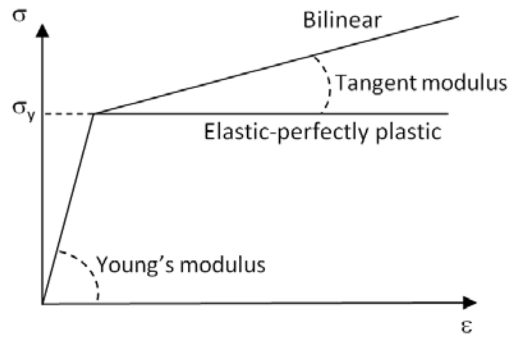

Figure 1: Two "*quick start*" approaches considered in the analysis.

Table 1: Mechanical properties for the "*quick start*" approach.

Material	Symbol	Value
Young Modulus	E	200GPa
Poisson Ratio	ν	0.3
Yield Stress	σ_Y	530MPa
Ultimate Stress	U	625MPa
Elongation	e	12%

According to [17], the Swift's [1] hardening model is defined as:

$$\sigma_y = \sigma_i \left(\varepsilon_0 + \varepsilon_p\right)^n , \tag{1}$$

where σ_i, ε_0 and n are the material parameters. Also from the same reference [17], Voce's modified hardening model is defined as:

$$\sigma_y = \sigma_0 + \zeta\varepsilon_p + \left(\sigma_\infty - \sigma_0\right)\left[1 - \exp\left(-\delta\varepsilon_p\right)\right] , \tag{2}$$

in which σ_0, σ_∞, δ and ζ are the hardening parameters obtained by an identification technique based on an Hybrid Genetic–BFGS optimization method [17]. Table 2 shows the hardening parameters for both equations, determined by using tensile tests with specimens prepared according to the Brazilian NBR-ISO 6892 standard.

Table 2: Material parameters identified by Stahlschmidt *et al*. [17], for the cold rolled steel used in this analysis.

Swift's yield curve		Voce's yield curve	
σ_i	1175.7 MPa	σ_0	425.9 MPa
ε_0	0.0018733*	σ_∞	720.66 MPa
n	0.1821	δ	34.9928
		ζ	552.25 MPa

*value corrected to accomplish for the elastic curve

3 SIMULATION DETAILS

All the simulations were performed with the use of the commercial FEM software ANSYS, version 12.1. A 2D approach using axis-symmetric formulation was used to model the NBR-ISO specimen, and plane strain for the ECAE process. The geometry selected for the ECAE workpiece was a square section with 10mm edge, and length of 40mm. The extrusion distance inside the die was 35mm in order to achieve a significant portion of the workpiece extruded. The element used in the simulations was an eight-node, non-linear quadratic element, referenced in ANSYS [16] as PLANE183. The die was modeled as rigid walls without heat transfer. Thermal effects were also not considered in the workpiece. The contact between the workpiece and die walls was modeled using Augmented Lagrangean´s Method [16], which is a combination of the pure penalty method in the tangential direction and pure Lagrange's Method in the normal direction [16]. Initially, it uses the contact stiffness state in the equilibrium. Afterwards, the resulting penetration is minimized by using the Lagrangean part of the algorithm. Coulomb friction was used to model the friction between the workpiece and die, which allows shear stresses on both contact surfaces.

4 RESULTS AND DISCUSSION

4.1 Results for the NBR-ISO workpiece

As a first analysis, in order to evaluate comparatively the different hardening rules, a simulation was performed for one of the geometries evaluated by Stahlschmidt *et al*. [17]. Figure 2 shows results for the equivalent plastic strain, plotted in the final stage of deformation. It is possible to observe that Voce´s model was the only one that could truly predict the actual deformation process of the workpiece. This is mainly because it is able to predict the final deformation region of the stress/strain curve, in which there is the neck formation and consequently the stress reduction. Nevertheless, it is also important to evaluate the loading force, once it is a major feature in stress analysis carried out by engineers in industry. Therefore, Figure 3 presents the comparison among the four models in terms of Force x Elongation. In this case, one first observation is that the elastic-perfectly plastic and bilinear models predict loading forces unrealistically smaller than the forces measured in the tensile tests [17]. As already observed by Stahlschmidt *et al*. [17], use of Swift´s model brings a better correlation, and Voce's model provides the best numerical results. Due to the best agreement with the experiments, when addressing the ECAE process, the latter should be considered as the reference when comparing the results obtained by using the other yield curves.

4.2 Simulation of the ECAE process

Most references describe the main influencing variables on the ECAE process as the angle between the channels, the inner and outer radii and the friction coefficient between the workpiece and the channel walls. According to the analysis performed by Krishnmaiah *et al.* [4]; Son, Jin and Im [6] and Hu, Zhang and Pan [8], a *"soft"* process would be performed using an angle of 120^{o} together with larger inner and outer radii and low friction coefficient. Considering the aforementioned conditions, two cases were evaluated, as indicated in Table 3.

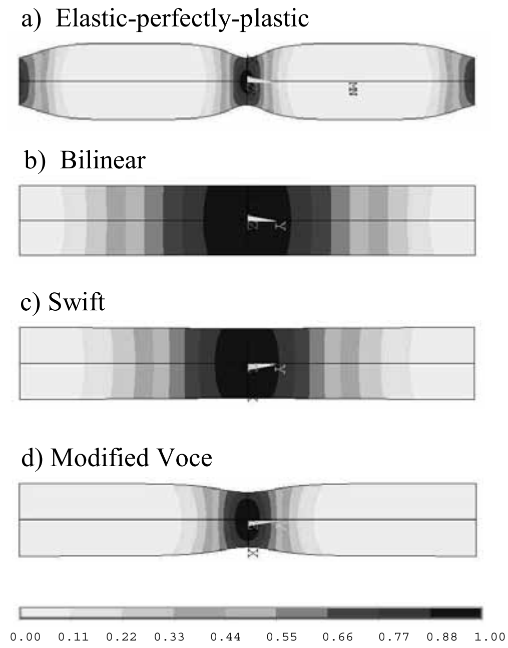

Figure 2: Normalized equivalent strain, $(\varepsilon - \varepsilon_{min}) / (\varepsilon_{max} - \varepsilon_{min})$, plotted on the deformed configuration.

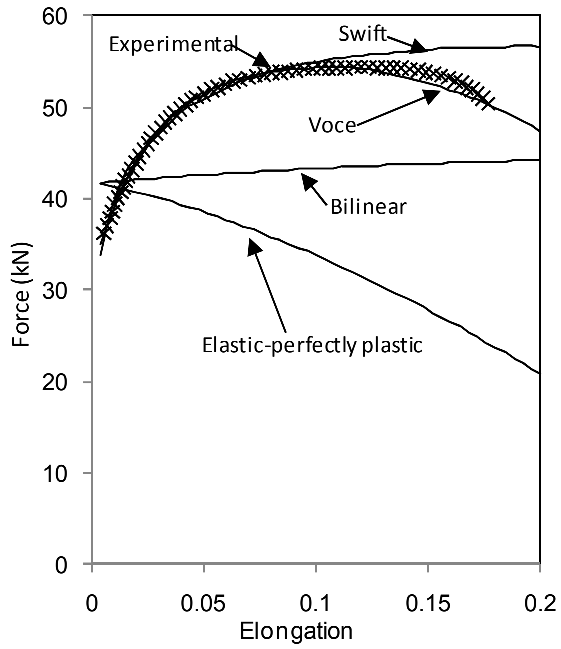

Figure 3: Force x Elongation curves for the hardening models compared to the experimental results [17].

Table 3: The *"soft"* and *"hard"* simulation parameters chosen for the comparison.

Parameter	*"soft"* process	*"hard"* process
Angle	120°	90°
Radii	2 and 5	0.2 and 2
Friction coefficient	0.05	0.15

The evaluated results were:

- Equivalent plastic strain and von Mises stress plotted on the deformed configuration.
- The extruding force and integrated work.
- The equivalent strain at the middle of the workpiece in the short and the long direction.
- The equivalent von Mises stress in the same directions.

Figure 4 presents the equivalent plastic strain and von Mises stress plotted on the deformed configuration for the *"soft"* process simulation. It can be clearly observed the region where the shear of the workpiece is taking place. Also, there is some major strain concentration at the upper side of it. One can also notice high von Mises stress concentration at the shear region and at the upper side.

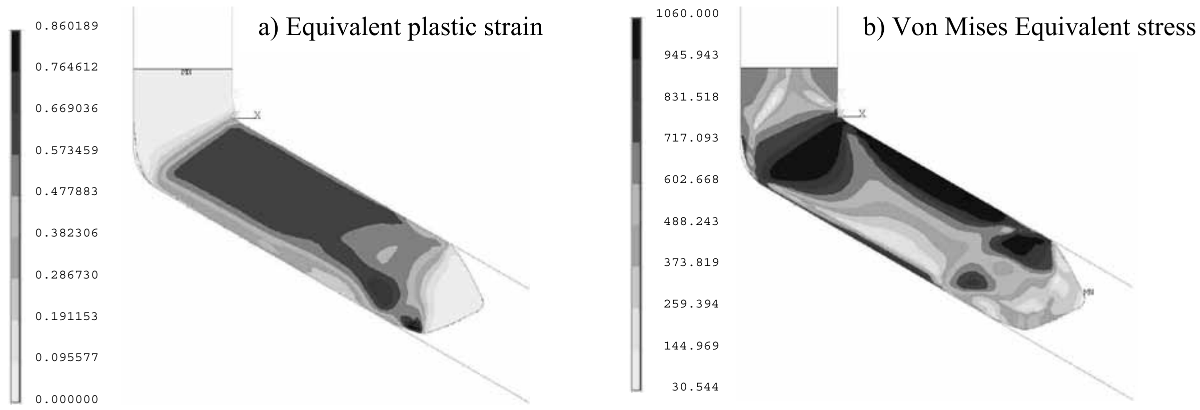

Figure 4: Results for the *"soft"* condition plotted on the deformed configuration for the modified Voce's model.

Figure 5 presents the equivalent plastic strain and equivalent von Mises stress plotted on the deformed configuration for the *"hard"* process simulation. In this case, the 45^{o} shear of the workpiece can be clearly observed, as well as the much higher strains and stresses compared to the *"soft"* condition. The maximum plastic strain achieved in this case is around 1.6, against 0.86 for the *"soft"* condition. The maximum von Mises stress is 1468 MPa, against 1060 MPa for the *"soft"* condition. It shows that the chosen *"soft"* and *"hard"* conditions are representative for the purpose of this analysis.

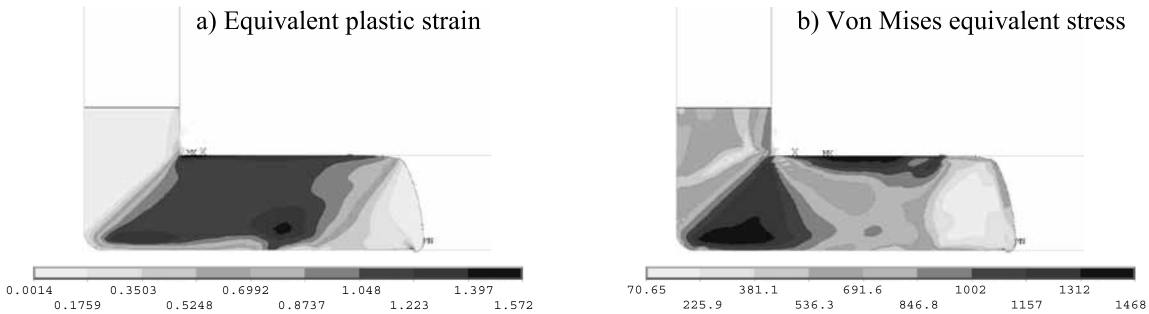

Figure 5: Results for the *"hard"* condition plotted on the deformed configuration for the modified Voce's model.

When comparing the results of the extrusion force for the two conditions and four hardening models considered, it can be observed in the figure 6 that, as expected, there is a huge difference between the *"soft"* and *"hard"* maximum forces necessary for performing the extrusion. For the *"soft"* condition, Figure 6a, Swift's model presents a fairly good agreement with modified Voce's equation, considering the latter as reference. Nevertheless, the bilinear model presented some qualitative similarity, but a lower force level. In the same case, elastic-perfectly plastic's model presented much lower results. The force results for the *"hard"* condition are presented in Figure 6b. It can be observed that Swift´s and Bilinear models present good correlation with Voce's equation, however, the results for the elastic-perfectly plastic's model were markedly unrealistic.

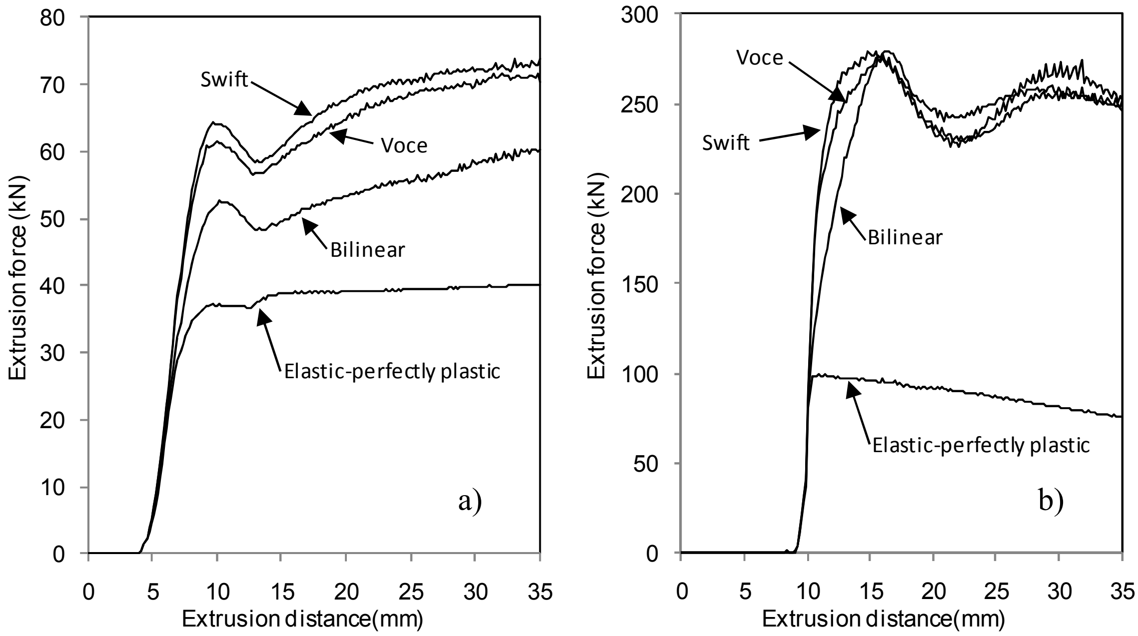

Figure 6: Comparison of the simulated extruding force using the four hardening models. a) *"soft"* condition. b) *"hard"* condition.

Table 4: Simulated extrusion work for the two conditions and four hardening models.

	Extrusion work [J]						
Condition	**Voce**	**Swift**	**Difference [%]**	**Bilinear**	**Difference [%]**	**Elastic-perfectly plastic**	**Difference [%]**
"soft"	12.3	12.9	4.9	10.6	-13.8	7.0	-43.1
"hard"	44.1	43.1	-2.3	44.0	-0.2	13.3	-69.8

As a resume of the observations, it is better to represent the total extrusion work, shown comparatively in Table 4. It can be observed that Swift´s and Bilinear models presented acceptable differences lower than 5% in the most cases. For the *"soft"* condition, Bilinear model presented a higher discrepancy of 13.8%, but still acceptable for a *"quick start"* approach. In the other hand, Elastic-perfectly plastic model presented discrepancies higher than 40%, which are completely unacceptable.

Figure 7a and b, show the equivalent plastic strain distribution along the centerlines of the workpiece for the *"soft"* condition. It can be observed that, for both horizontal and vertical directions, there is a good agreement of Voce's, Swift's and Bilinear models. Elastic-perfectly plastic model predicts higer plastic strain levels, and a more uniform distribution. The reason lies on the fact that once the yield stress is reached during the simulation process, a further increase on the load would cause continuous plastic deformation without any hardening. For the *"hard"* condition, Figure 7c and d, one may notice that in the horizontal direction, the plastic strain at the lower and upper regions of the workpiece was more affected by the models, whereas a smaller effect was observed inside the workpiece. In the vertical direction, major differences were found at the lower part, which is the region directly affected by the initial deformation experienced by the workpiece when introduced in the angular channel. It is reasonable to expect that the hardening rule is more influent in this region.

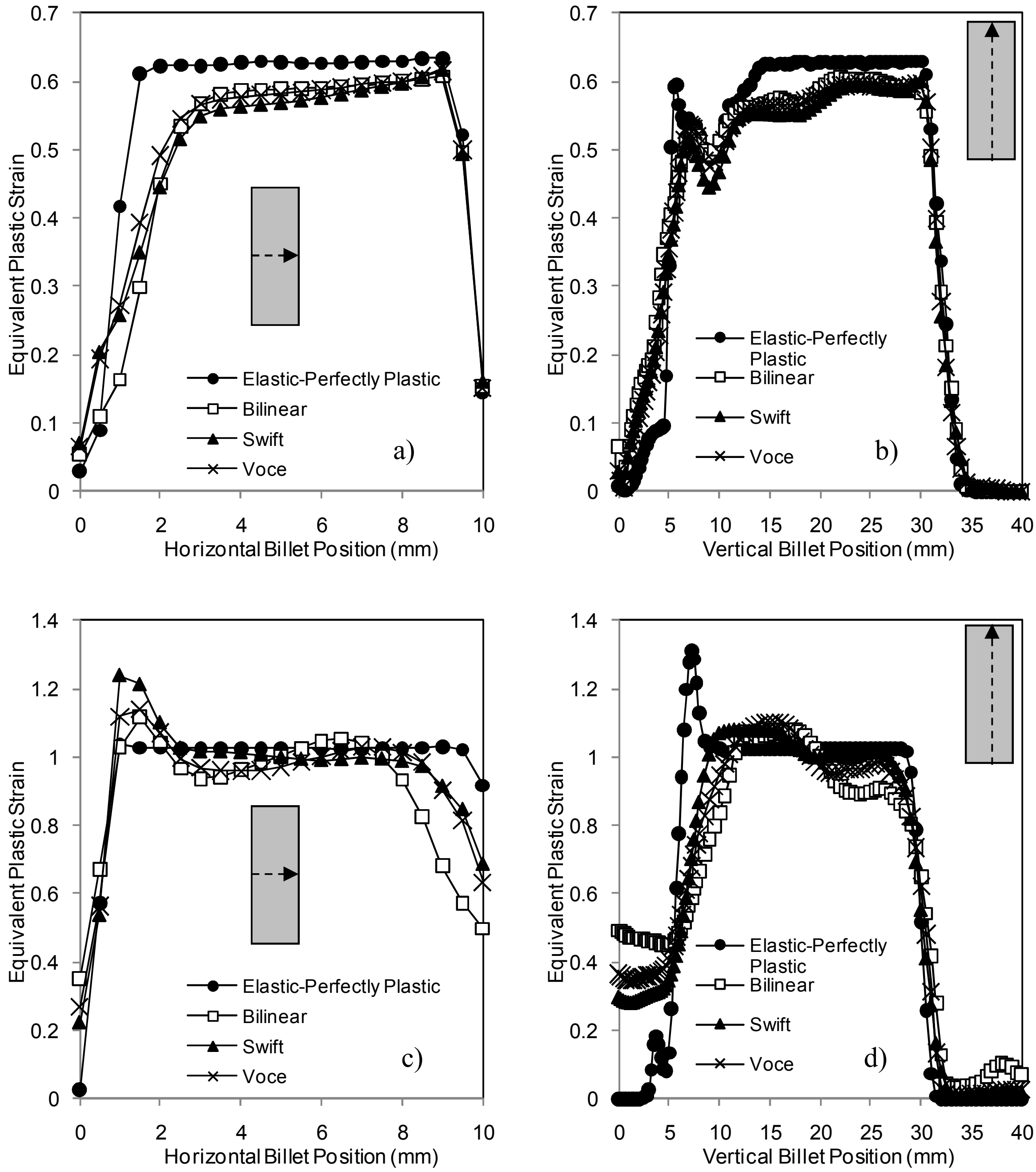

Figure 7: Equivalent plastic strain for the two conditions along the horizontal and vertical centerlines. a) *"Soft"* condition – horizontal. b) *"Soft"* condition – vertical. c) *"Hard"* condition – horizontal. d) *"Hard"* condition – vertical.

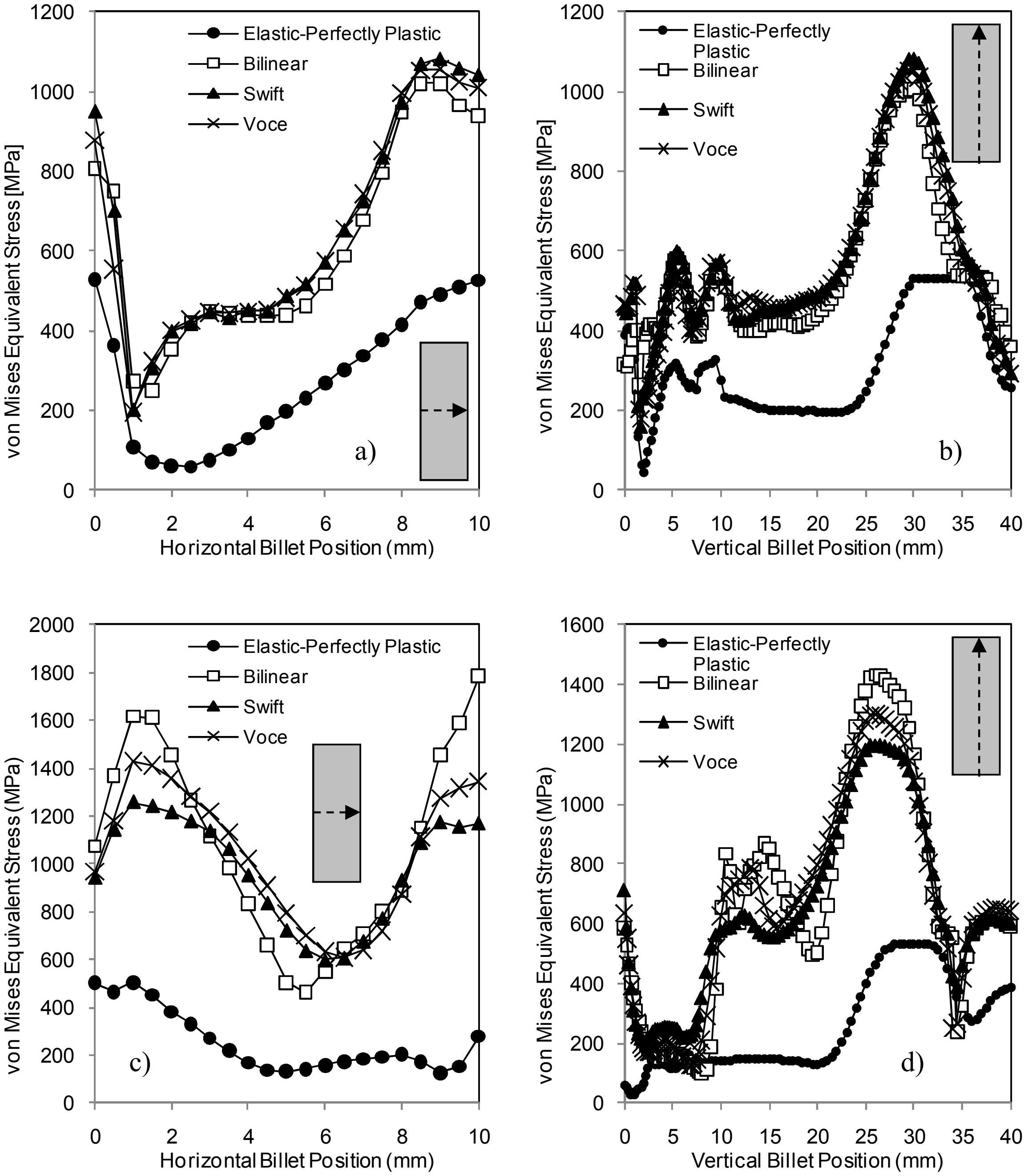

Figure 8: von Mises equivalent stress for the two conditions along the horizontal and vertical centerlines. a) *"Soft"* condition – horizontal. b) *"Soft"* condition – vertical. c) *"Hard"* condition – horizontal. d) *"Hard"* condition – vertical.

The comparison has also been performed for the stress results, once, in many cases, it is important to evaluate the residual stresses present in the workpiece after each passage through the angular channel. It can be observed in Figure 8a and b that, for the *"soft"* condition, Swift's and Bilinear models yield good agreement with the reference along horizontal and vertical directions; however the Elastic-perfectly plastic model presented a huge difference. The same behaviour can be observed in Figure 8c and d for the *"hard"* condition. Although presenting much higher stress levels, there is also for this condition a good agreement with the reference for Swift's and Bilinear models, whilst the Elastic-perfectly plastic material presented larger differences.

12 CONCLUSIONS

Within the industrial perspective, when conceiving new forming operations, designing new mechanical components or using new materials, research engineers generally use a modeling strategy known as "*quick start*". In such cases, in a first stage, material is described in a simplified manner in order to obtain preliminary results used to validate or not the design concept. In a second stage, experiments aiming at determining material parameters are designed and new round of simulations are performed aiming at achieving the primary design objectives. This work is inserted within this framework, which aims to assess simplified material models against a more complex constitutive relation and determine how accurate are the results obtained using such models.

- The ECAE process was used in this article to compare four different yield curves: modified Voce, Swift, Bilinear and Elastic-perfectly plastic. The main objective was to determine whether a simpler yield curve could be used in conjunction with the ECAE process, which in turn, is recommended to achieving better mechanical properties for materials.
- Voce's and Swift's parameters were taken from Stahlschmidt *et al*. [17], which were determined by applying optimization methods. In the reference, Voce's hardening model presented the best agreement with the experimental results and was used in the present work as a reference for comparison.
- The results were compared based on three information normally required during the planning phase of the ECAE process: the required extrusion force and work, plastic strains and residual stresses present in the workpiece.
- Swift's equation presented good correlation with the reference (modified Voce) in most cases, but as well as the latter, requires initial experimental testing for determining parameters for the simulation.
- The Bilinear model requires only the knowledge of five properties: Young Modulus; Poisson's ratio; Yield and Ultimate stresses and elongation, which, in most cases, can easily be found in the literature or web sites. This approximation presented a fairly good correlation with Voce's model. Therefore, it is a good choice for this initial evaluation of the ECAE process and its desired results.
- The elastic-perfectly plastic´s model presented a very poor agreement with Voce's results, thereby indicating that it is a bad choice, mainly for the type of material considered in the analysis. Some hardening needs to be considered with the risk of making poor predictions for the process planning.

REFERENCES

[1] Swift, H.W. Plastic instability under plane stress. *J Mech. Physics Solids* (1952) **1**:1-18.
[2] Voce, E. The relationship between stress and strain for homogeneous deformation, *J. Inst.*

Metals (1948), **74**:537-562.

[3] Segal, V.M. Materials processing by simple shear, *Mat. Sci. Eng*. (1995) **A197**:157-164.

[4] Krishnaiah, A.; Kumaran, K.; Chakkingal, U. and Venugopal, P., Finite element analysis of equal channel angular extrusion (ECAE) process, *Metallurgical and Materials Engineering* (2004) **1**:1-8.

[5] Aour, B.; Zairi, F.; Gloaguen, J.; Naitabdelaziz, M. and Lefebvre, J. Numerical investigation on equal channel angular extrusion process of polymers, *Computational Materials Science* (2006) **37(4)**:491-506.

[6] Son, I.H.; Jin, Y.G. and Im, Y.T. Finite element investigations of friction condition in equal channel angular extrusion, *Journal of Achievements in Materials and Manufacturing Engineering* (2006) **17(1-2) Jul-Aug**:285-288.

[7] Lee, J.; Son, I.; Im, Y.; Chon, S. and Park, J. Design guideline of multi-pass equal channel angular extrusion for uniform strain distribution, *Journal of Materials Processing Technology* (2007) **191(1-3)**:39-43.

[8] Hu, H.-jun; Zhang, D.-fei and Pan, F.-sheng. Die structure optimization of equal channel angular extrusion for AZ31 magnesium alloy based on finite element method, *Transactions of Nonferrous Metals Society of China* (2010) **20(2)**:259-266.

[9] Nagasekhar, A.V.; Yoon, S.C.; Tick-Hon, Y. and Kim, H.S. An experimental verification of the finite element modeling of equal channel angular pressing, *Computational Materials Science* (2009) **46(2)**:347-351.

[10] Kaushik, A.; Karaman, I. and Srinivasa, A.R. Simulation of powder compaction using equal channel angular extrusion at room temperature: Comparison of two constitutive theories, *International Journal* (2009) **1(1)**:211-226.

[11] Gurson, A.L. Continuum theory of ductile rupture by void nucleation and growth: Part I – Yeld criteria and flow rules for porous ductile materials, *Journal of Engineering Materials and Technology* (1977) **99**:2-15.

[12] Duva, J.M. and Crow, P.D. The densification of powders by power-law creep during hot isostatic pressing, *Acta Metallurgica Et Materialia* (1992) **40(1)**:31-35.

[13] Semiatin, S. and Delo, D., Equal channel angular extrusion of difficult-to-work alloys, *Materials & Design* (2000) **21(4)**:311-322.

[14] Yang, Y. and Lee, S. Finite element analysis of strain conditions after equal channel angular extrusion, *Journal of Materials Processing Technology* (2003) **140(1-3)**:583-587.

[15] Stahlschmidt, J. *Parameter Identification of Elastic-Plastic Parameters*, M.Eng. Dissertation, UDESC, Joinville, (2010).

[16] ANSYS Manual, Release 12.0 - © (2009).

[17] Stahlschmidt, J.; Vaz Jr., M.; Muñoz-Rojas, P.A. and Cardoso, E.L. Uma estratégia numérico-experimental para a determinação de parâmatros materiais, *6th Brazilian Conference on Manufacturing Engineering* (2011).

[18] AISI 1045 Steel, cold drawn, 19-32 mm (0.75-1.25 in) round, <http://www.matweb.com/search/DataSheet.aspx?MatGUID=cbe4fd0a73cf4690853935f52d910784&ckck=1>, visited on Apr/30th/2011.